Observation of a family of all-charm tetraquarks at CMS

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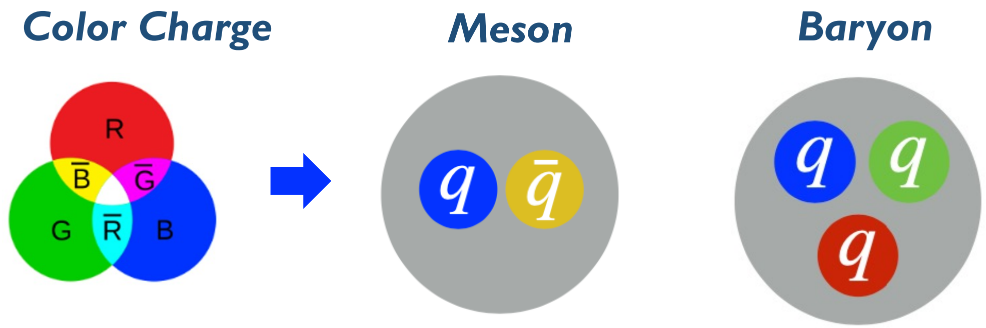
第八届全国重味物理与量子色动力学研讨会

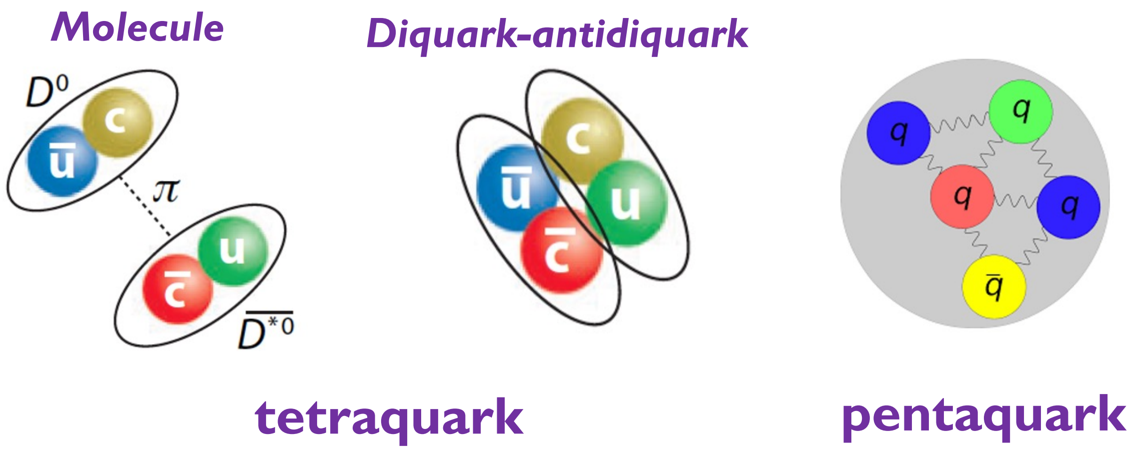
The quark model

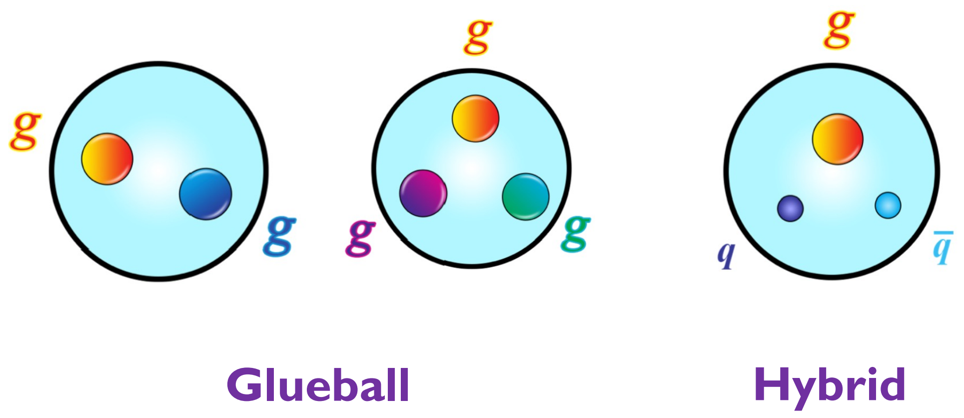
Classical quark model



- **> 60 years of classical quark model**
  - Experimentally tested at high energies; asymptotic freedom →Nobel Prize 2004
  - Success of Conventional Hadrons at low energies: non-perturbative quark model (confinement) →Nobel Prize 1969
- **Exotic hadrons (Non-Conventional), no definitive conclusion yet**
  – currently a hot topic

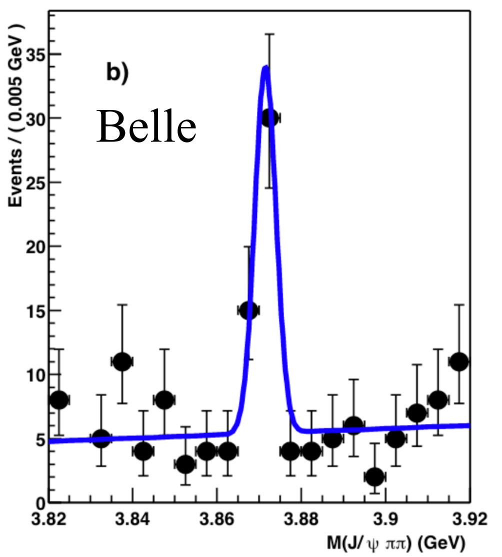
"Exotic" hadron



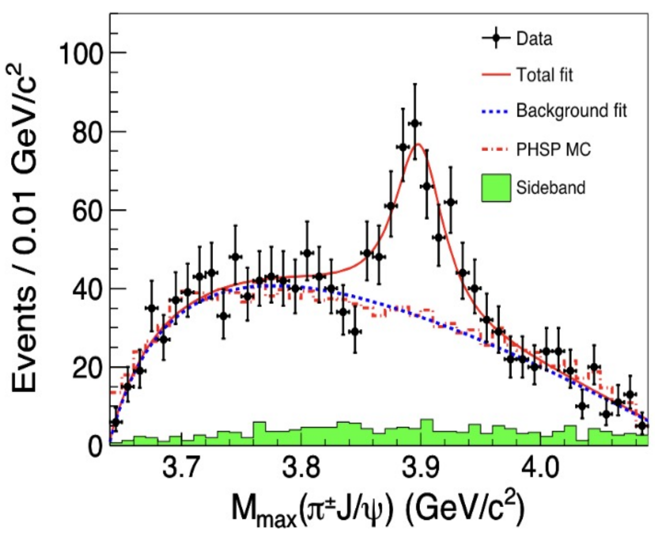


Heavy-Flavor Exotic Hadron States (XYZ Particles)

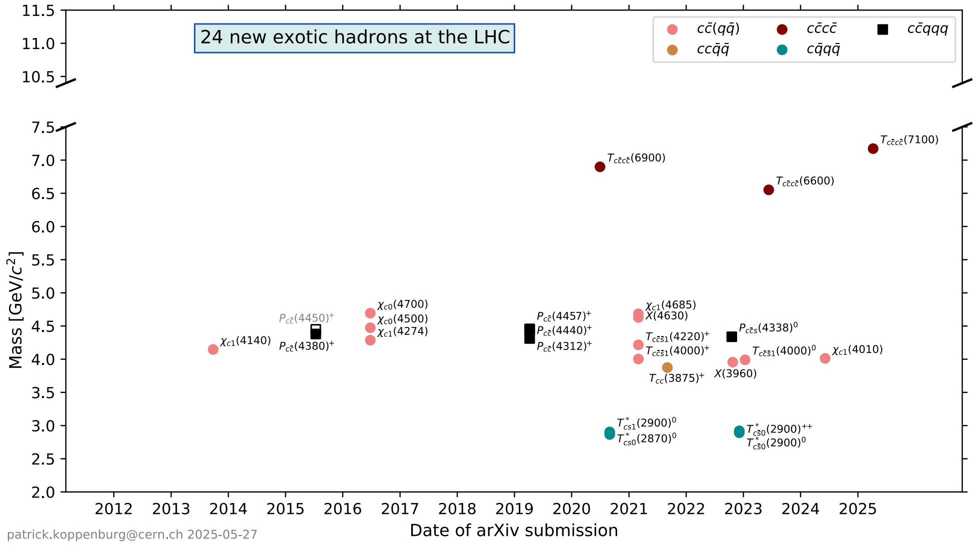
X(3872) [$uc\bar{u}\bar{c}$]



$Z_c^+(3900)$



24 exotic hadrons at LHC



- **Light exotics** likely exist, but too messy for clear identification
- **Heavy-flavor exotics**: larger quark mass relative to Λ_{QCD}, theoretical treatments more reliable

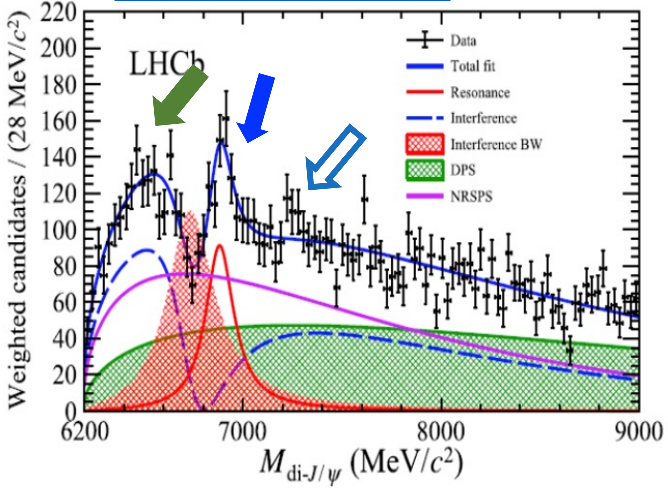
  X(3872), kicked off a boom in (heavy-flavor) exotic hadron, dozens of XYZ found

  Z_c(3900), carries charge and couples to charmonium

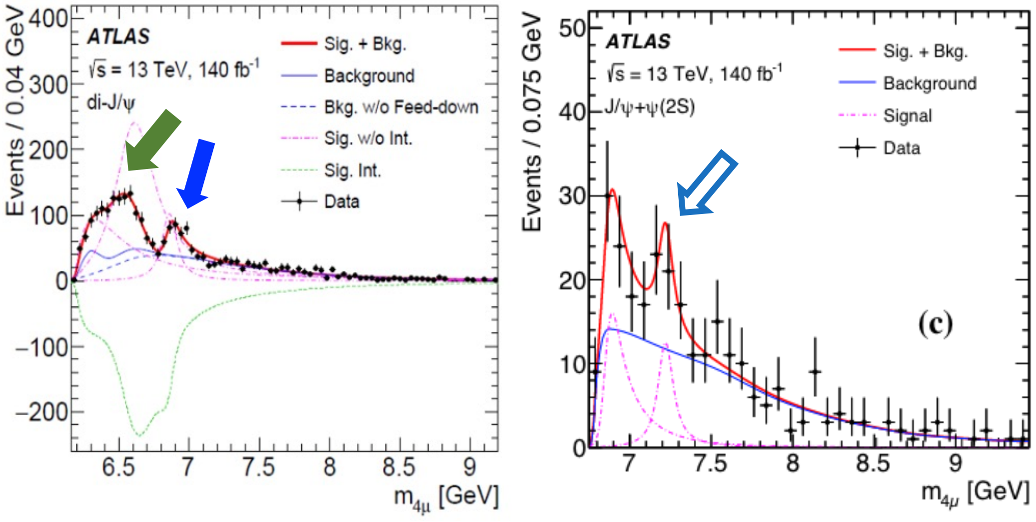
- **Fully-heavy exotic hadrons,** promising and accessible for theoretical exploration

Status of all-charm tetraquark

Sci. Bull., 65(23):1983, 2020



Phys. Rev. Lett., 131(15):151902, 2023



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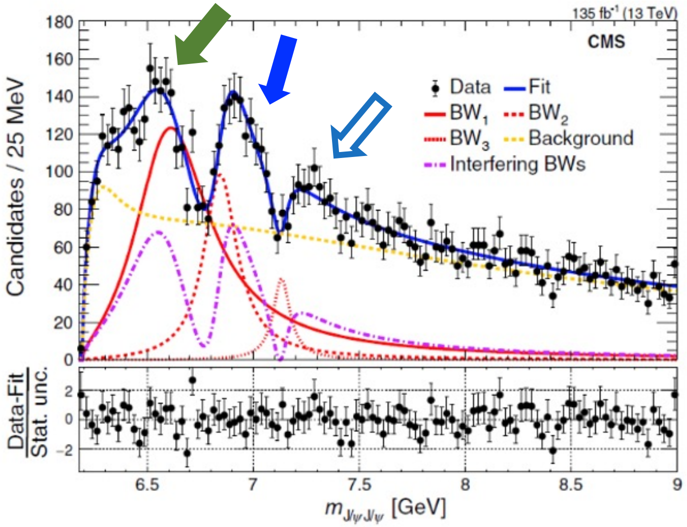

- All exp observe X(6900)
  - + additional structures:
    - Hump @ 6.6 GeV: Different modeling
    - Hint @ 7.2 GeV: LHCb not consider; ATLAS 3σ hint in $J/\psi\psi(2S)$
- CMS first observed X(6600) & evidence of X(7100)

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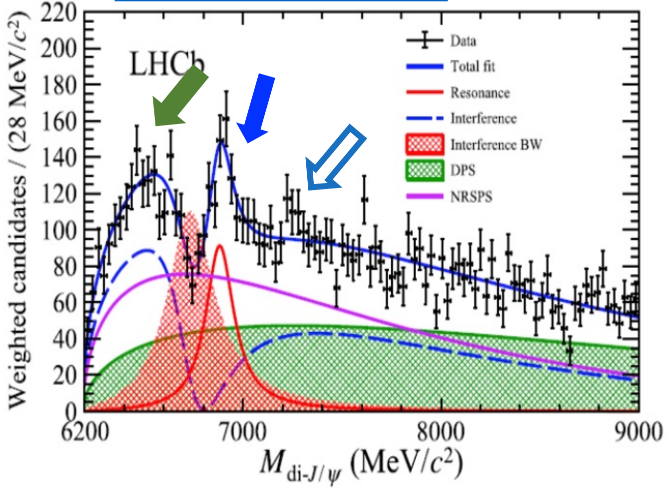

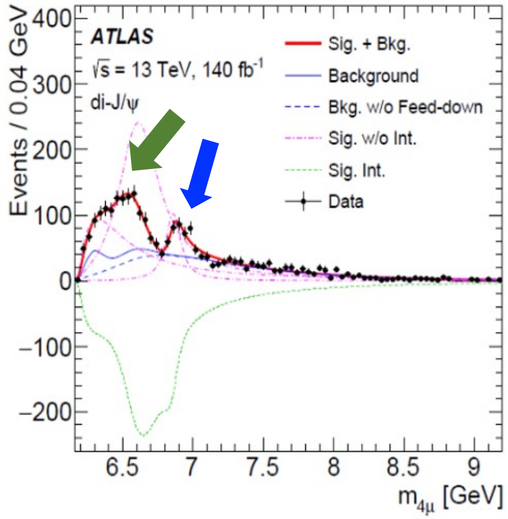

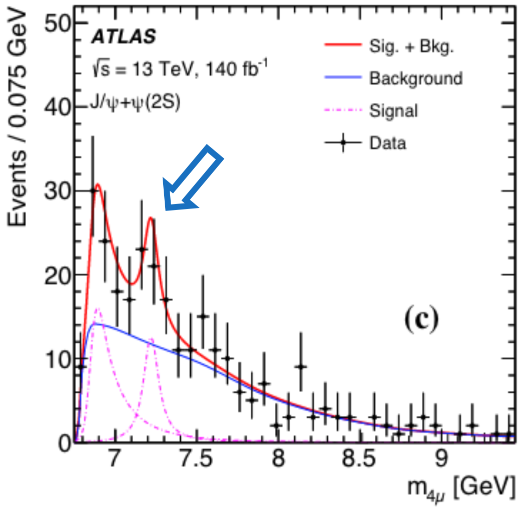

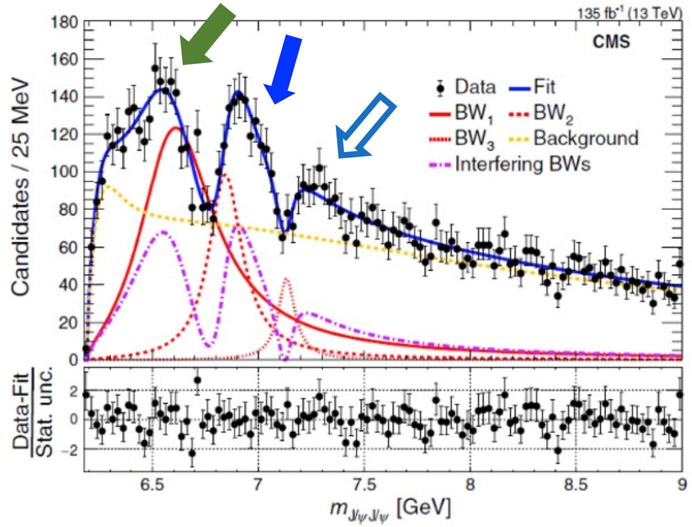

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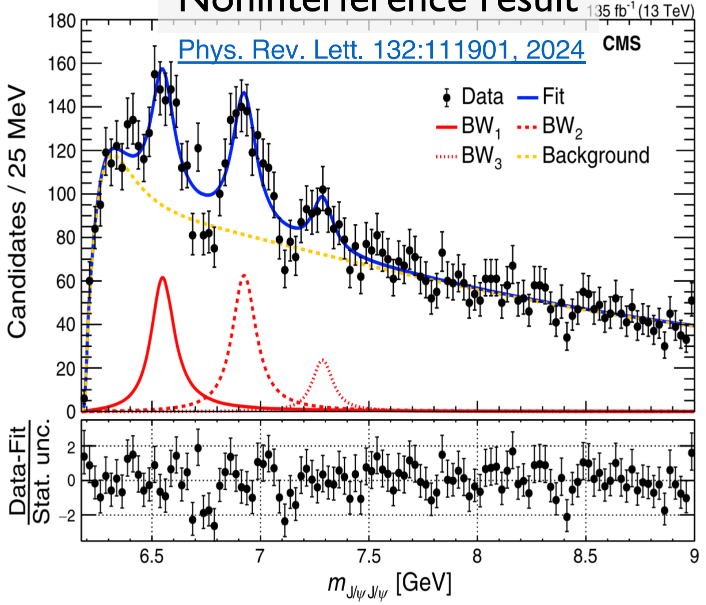
- All exp use interference, but in diff ways:
  - LHCb: extra BW interfere with SPS, X(6900) NOT interfering
  - ATLAS and CMS: different multi-resonance interference

🔎A number of unresolved questions !

Noninterference result



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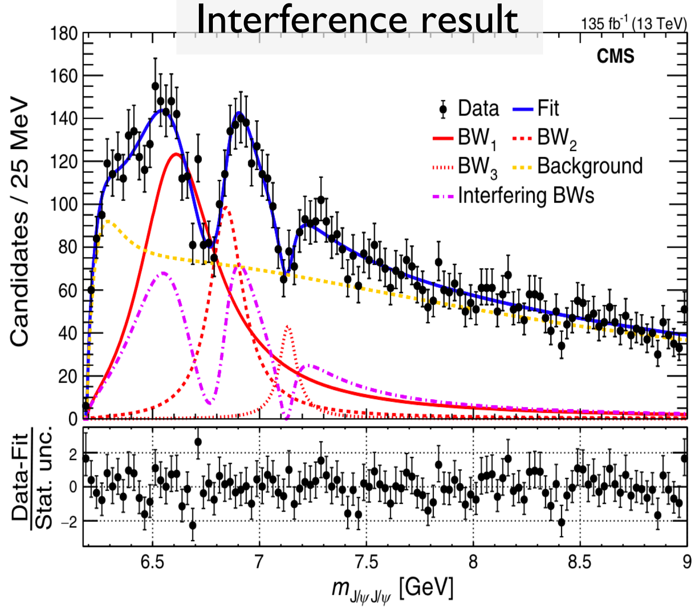

- **CMS Run 2 Results**

  Data: Run 2 135 fb^{-1} (2016-2018)

  X(7100): 4.7σ

  Interference < 4σ

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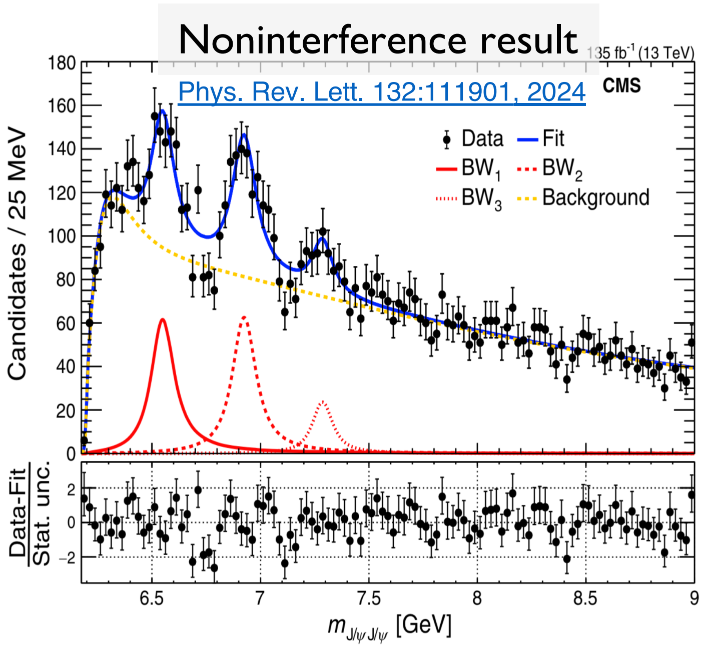
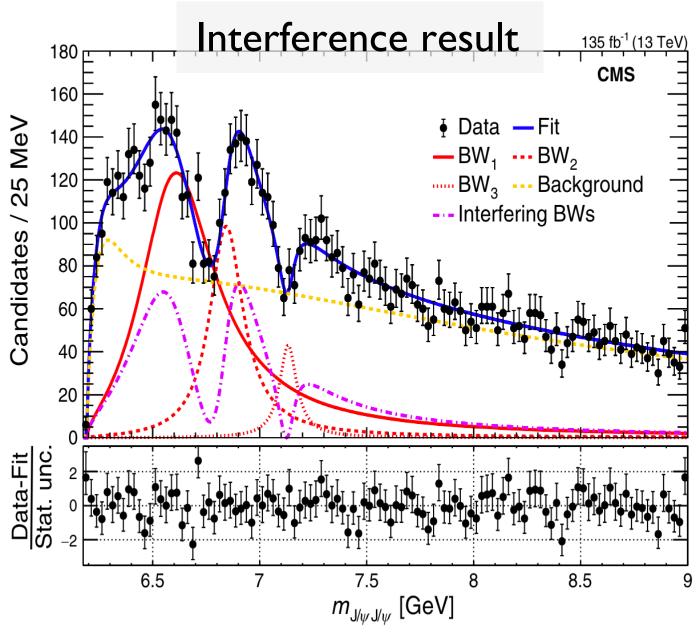
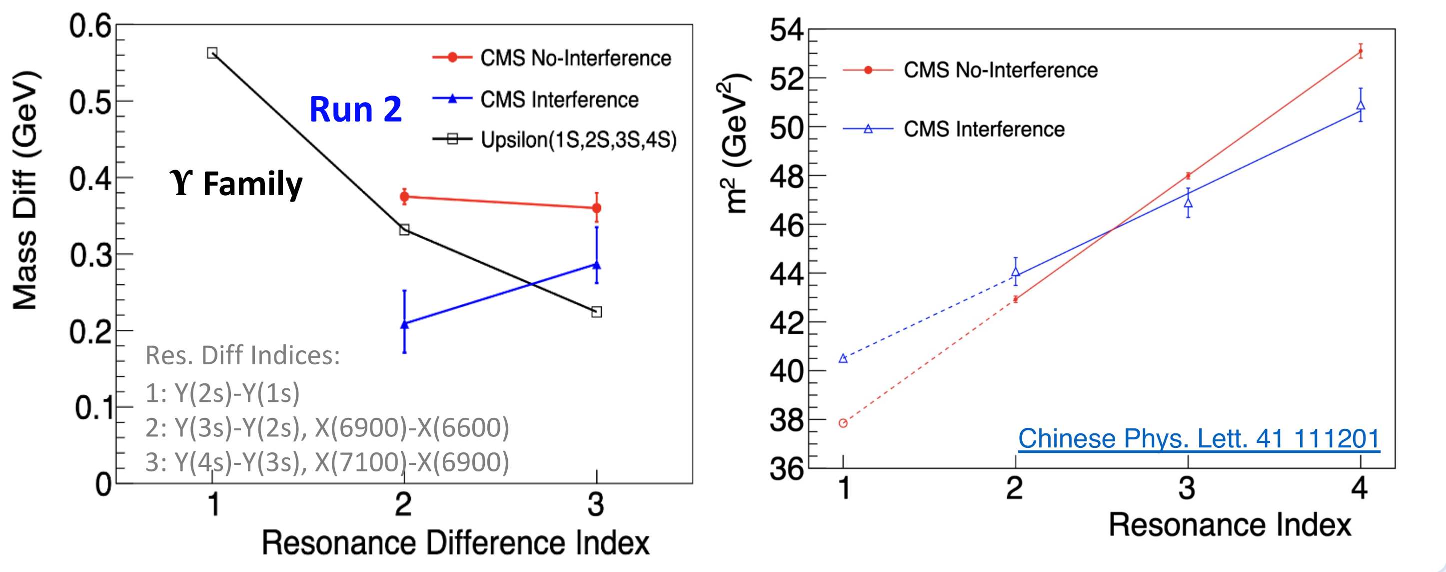




CMS Run 2 Regge plot



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Interference < 4σ

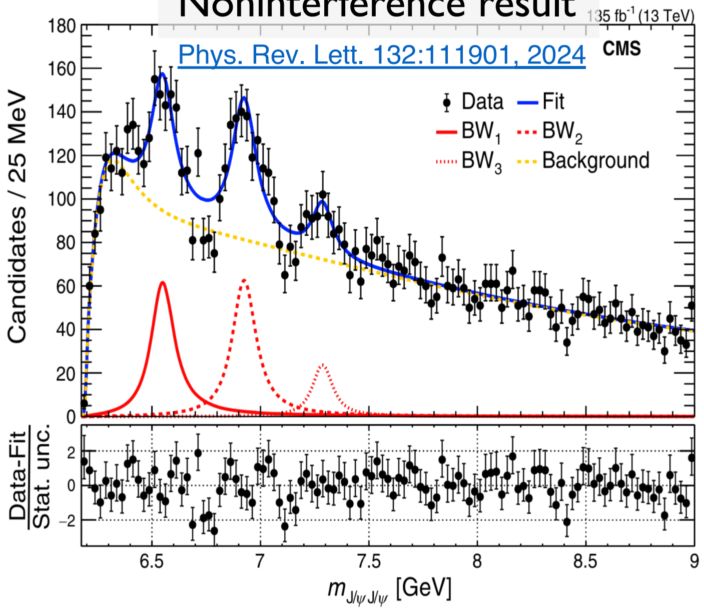
- ➢ All three resonances?
- ➢ Interference?

  ==> same J^{PC} quantum numbers
- ➢ > 200 MeV mass splittings

  ==> Radial excitations ?

Cornell Model: $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r + \ldots$

Noninterference result



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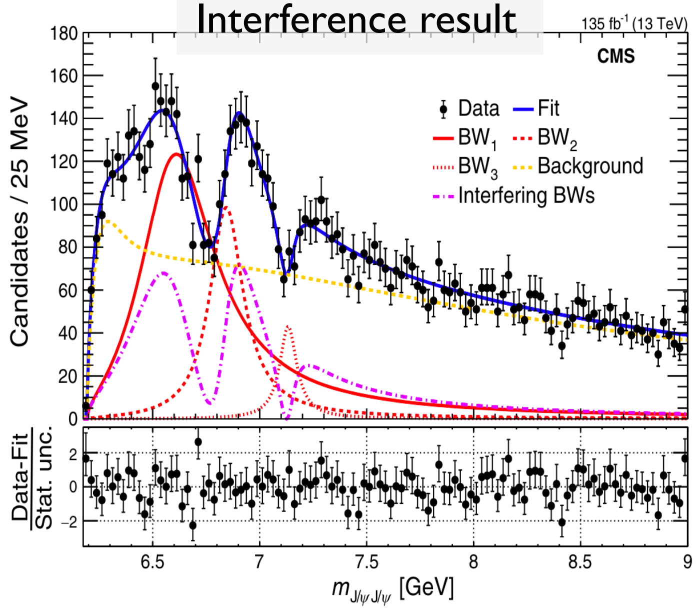

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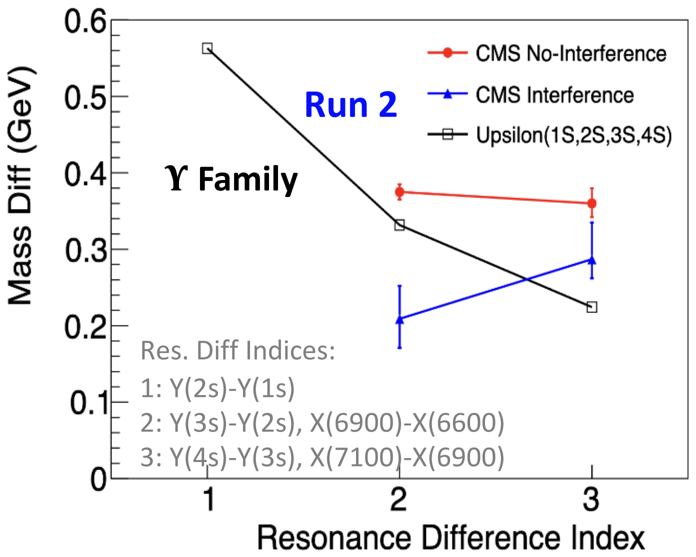

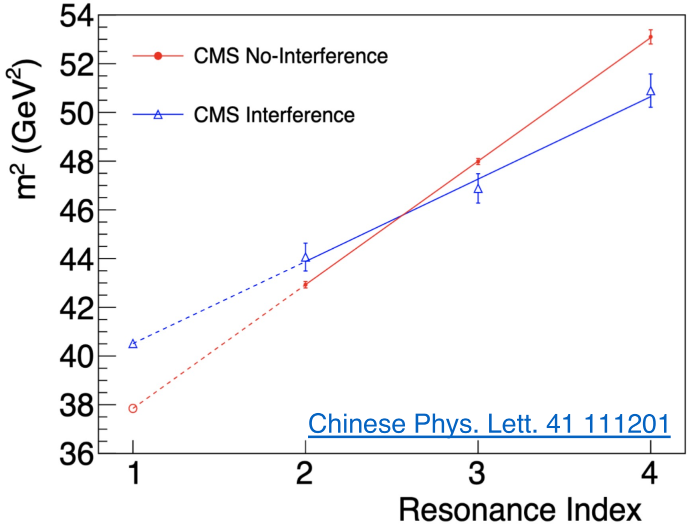

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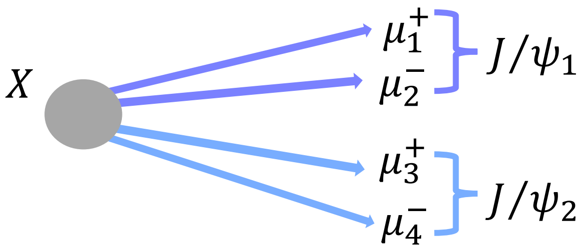
A radial family of all-charm tetraquark states with same J^{PC} ?

$J/\psi J/\psi$ updated result with CMS Run 2 and 3 data

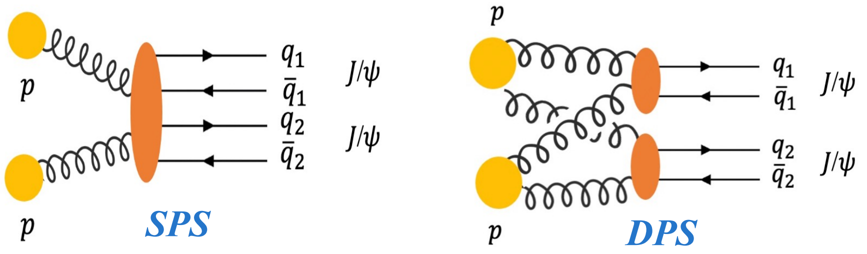
- Data samples [315 fb^{-1}]
  - Run 2: 135 fb^{-1} data taken in 2016, 2017 and 2018.
  - Run 3: 180 fb^{-1} data taken in 2022, 2023 and 2024.



- Signal

  $\mathrm{X} \rightarrow \mathrm{J}/\psi\mathrm{J}/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$

- Backgrounds
  - Non-resonant single-parton scattering(NRSPS)
  - Non-resonant double-parton scattering(NRDPS)



  - Feeddown from higher mass states
    i.e. $\mathrm{X}(6900) \rightarrow \mathrm{J}/\psi\psi(2S) \rightarrow \mathrm{J}/\psi\mathrm{J}/\psi + \text{anything}$
  - Combinatorial background
  - Enhancement near threshold, BW0

- Triggers

  HLT_Dimuon0_Jpsi3p5_Muon2
  - Level 1 requirements: 3 muons
  - $2.95 < M(\mu^+\mu^-) < 3.25\ GeV$
  - $p_T(\mu) > 3.5\ GeV$

  HLT_DoubleMu4_3_LowMass
  - Level 1 requirements: 2 muons
  - $0.2 < M(\mu^+\mu^-) < 8.5\ GeV$
  - one muon $p_T(\mu) > 4\ GeV$ and the other $p_T(\mu) > 3\ GeV$
  - $p_T(\mu^+\mu^-) > 4.9\ GeV$

Statistics of CMS Run 2+3

Follow Run 2 cuts + A new trigger for Run 3

❑ Single muon:

- Soft muon ID
- $|\eta(\mu)| \leq 2.4$

❑ Double muon:

- $2.95 < M(J/\psi) < 3.25\ GeV$
- $prob_{vtx}(J/\psi) > 0.1\%$ $M(\mu^+\mu^-)$ constrained to $M(J/\psi)$
- Final mass window cut for J/ψ candidate:

$$|M(\mu^+\mu^-) - M(J/\psi)| < 3\rho\sigma$$

❑ Four muons:

- 4μ charge should be zero
- $prob_{vtx}(4\mu) > 0.5\%$
- $prob_{vtx}(J/\psi J/\psi) > 0.1\%$

❑ Multiple candidates treatment:

- Select best combination from one 4μ candidate based on min.

$$\chi_m^2 = \left(\frac{m_1(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_1}}\right)^2 + \left(\frac{m_2(\mu^+\mu^-) - M_{J/\psi}}{\sigma_{m_2}}\right)^2$$

- Keep duplicate combination if pairs have non-overlapping muons

Baseline mass variable

– invariant mass of two constrained J/ψ candidates

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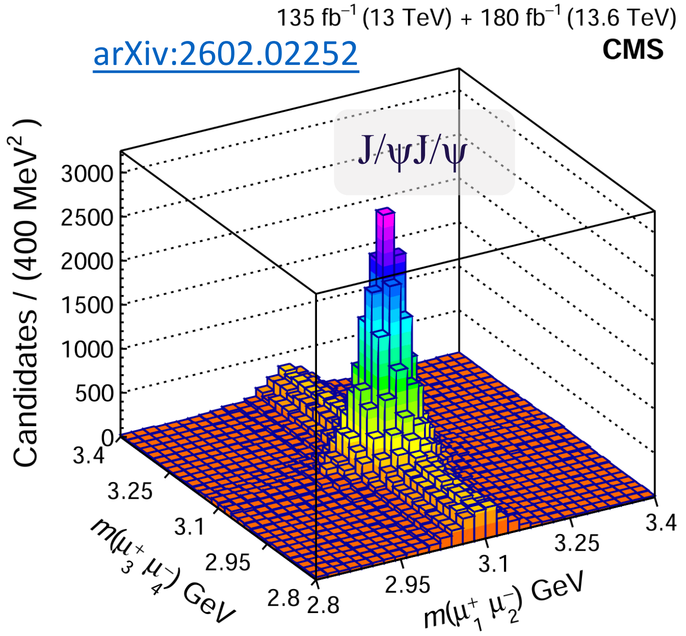
arXiv:2602.02252



❖ **J/ψJ/ψ yield from 2D fit**

Run 2 ~12622 ± 165

Run 3 ~31802 ± 476

Thanks to dimuon trigger !

❖ **Run 2+3 J/ψJ/ψ yield is 3.6X of Run 2**

❖ **Run 2+3 luminosity is 2.3X of Run 2**

Baseline mass variable

– invariant mass of two constrained J/ψ candidates

- Signal shape

  Relativistic Breit-Wigner

$$BW(m;m_0,\Gamma_0) = \frac{\sqrt{m\Gamma(m)}}{m_0^2 - m^2 - im\Gamma(m)},$$

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \frac{m_0}{m} \left(B'_L(q,q_0,d)\right)^2$$

- Background component

  NRSPS + NRDPS + Feed-down + Combinatorial + BW0

- Noninterference model

  NRSPS + NRDPS + Comb + Feed-down + BW0 + **BW1 + BW2 + BW3**

$$Pdf(m) = \sum N_{X_i} \cdot |BW(m, M_i, \Gamma_i)|^2 \otimes R(M_i) + N_{NRSPS} \cdot f_{NRSPS}(m)$$
$$+N_{NRDPS} \cdot f_{NRDPS}(m) + N_{Comb} \cdot f_{Comb}(m) + N_{Feedown} \cdot f_{Feeddown}(m)$$

- Interference model:

  NRSPS + NRDPS + Comb + Feeddown + BW0 **+ BW123 Interf. Term**

$$Pdf(m) = N_{X_0} \cdot |BW_0|^2 \otimes R(M_0)$$
$$+ N_{X\ and\ interf} \cdot |r_1 \cdot \exp(i\phi_1) \cdot BW_1 + BW_2 + r_3 \cdot \exp(i\phi_3) \cdot BW_3|^2$$
$$+ N_{NRSPS} \cdot f_{NRSPS}(m) + N_{DPS} \cdot f_{DPS}(m)$$
$$+ N_{Feeddown} \cdot f_{Feeddown}(m) + N_{Comb} \cdot f_{Comb}(m),$$

❖ Noninterference model

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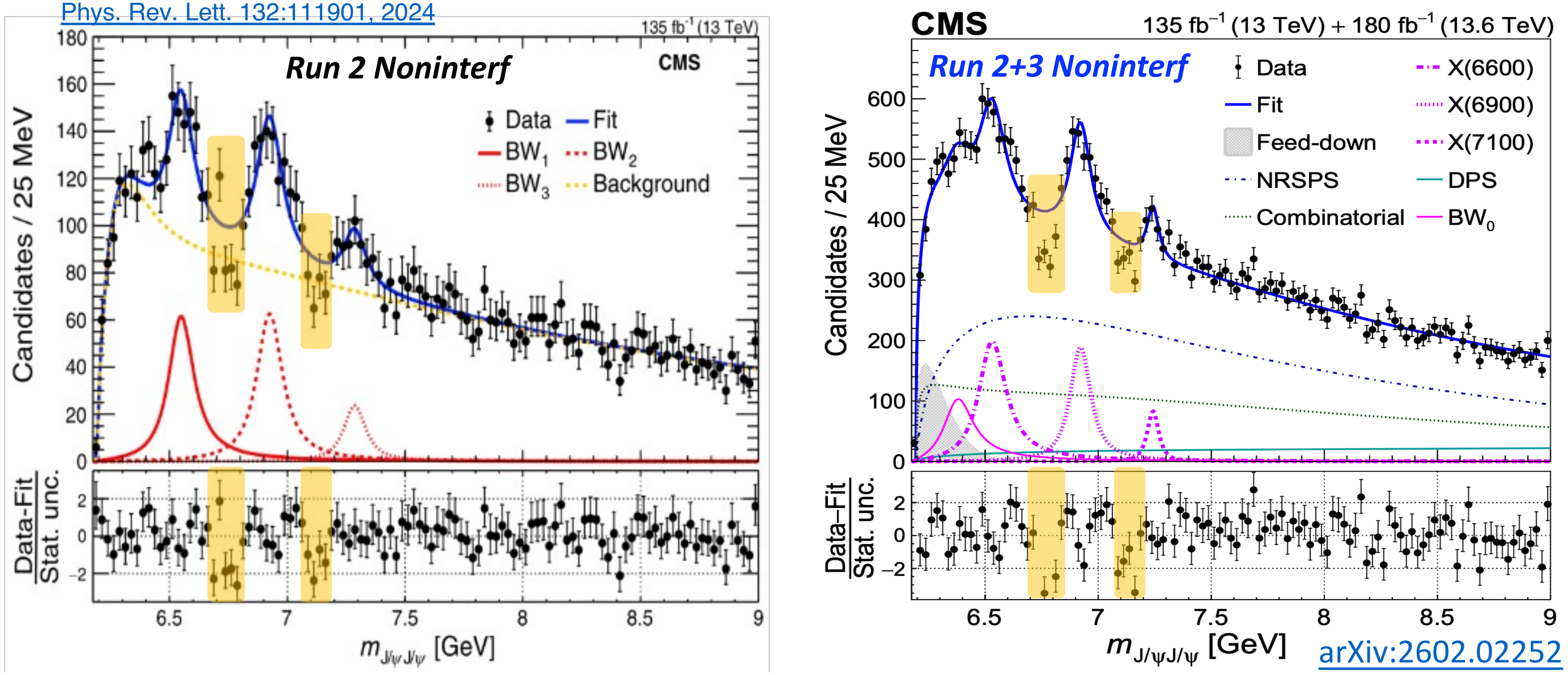
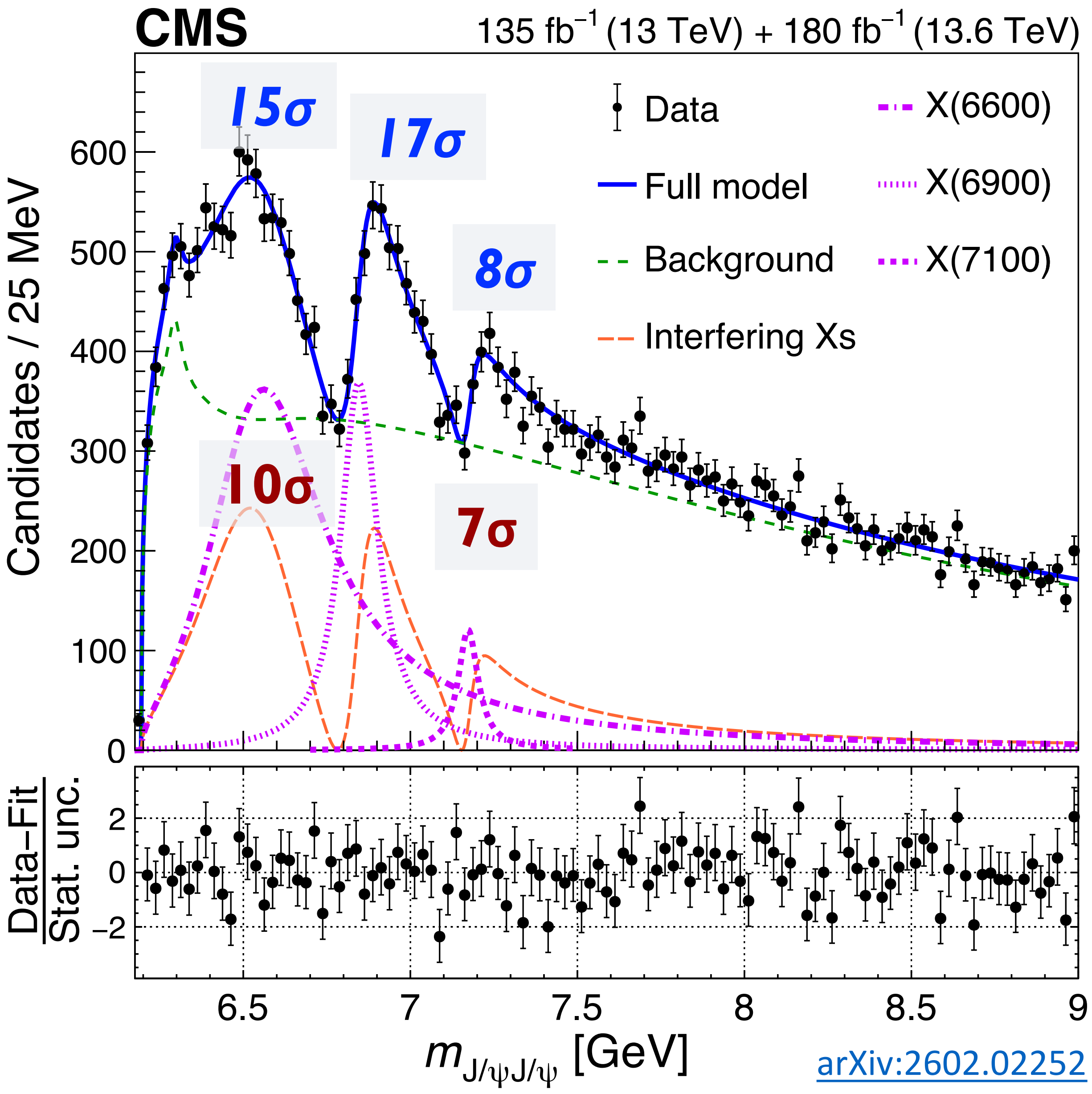


arXiv:2602.02252

Dips poorly described --- Noninterference model no longer sufficient



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Params [MeV]	Run II&III Interf.	Run II Interf.
M(BW1)	$6593^{+15}_{-14} \pm 25$	6638^{+43+16}_{-38-31}
Γ(BW1)	$446^{+66}_{-54} \pm 87$	$440^{+230+110}_{-200-240}$
M(BW2)	$6847 \pm 10 \pm 15$	6847^{+44+48}_{-28-20}
Γ(BW2)	$135^{+16}_{-14} \pm 14$	191^{+66+25}_{-49-17}
M(BW3)	$7173^{+9}_{-10} \pm 13$	7134^{+48+41}_{-25-15}
Γ(BW3)	$73^{+18}_{-15} \pm 10$	97^{+40+29}_{-29-26}

Precision improved by factor of 2~3

Large mass splittings, > 250 MeV

First observation of X(7100) in $J/\psi J/\psi$ channel

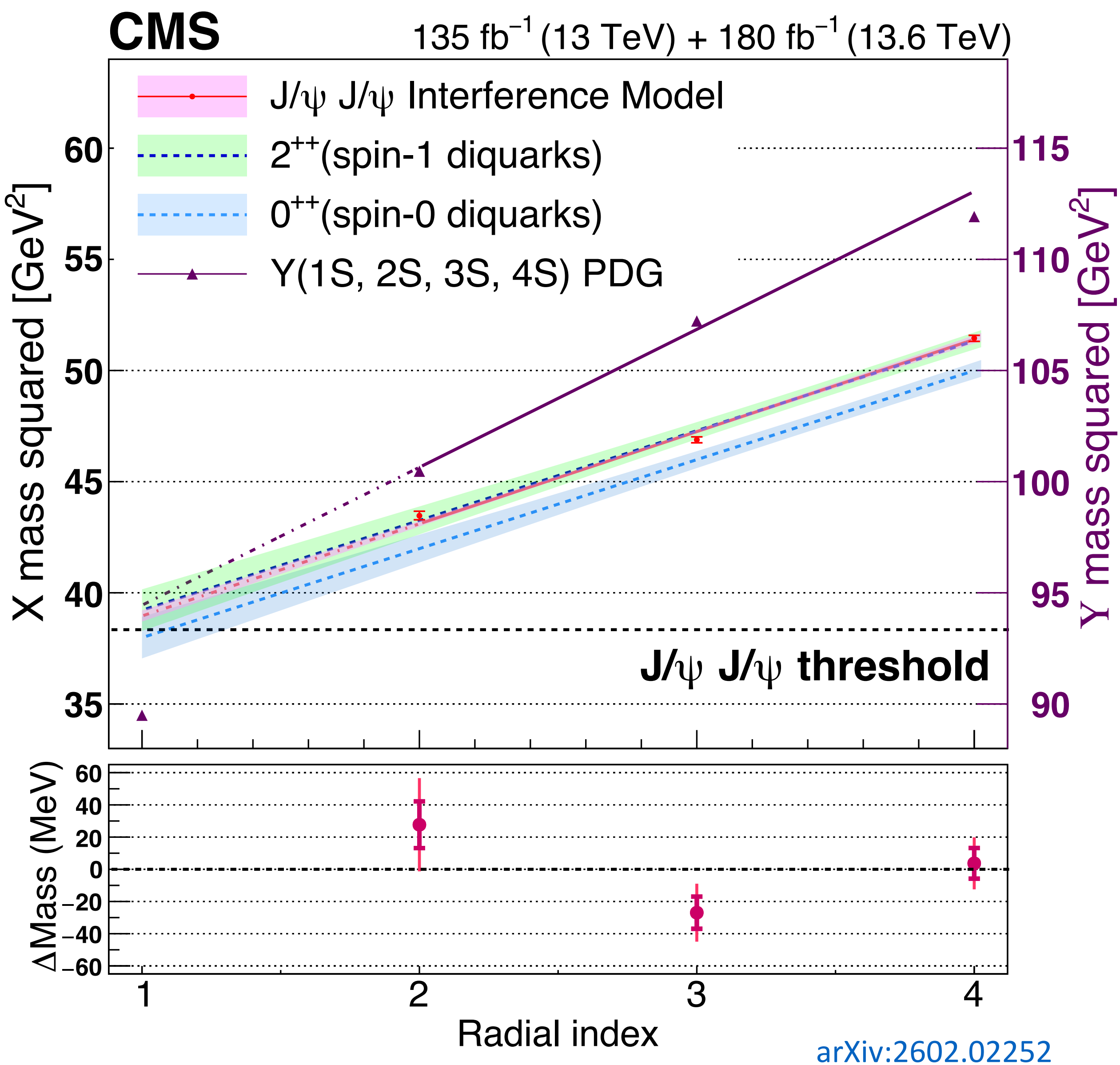
First observation of interference among X(6600), X(6900), and X(7100)

- Large X-mass splittings are characteristic of radial excitations
- In Regge theory : $n_r = \beta M^2 + \beta_0$

m^2: mass square
$n_r = n - 1$, n is radial quantum number
2, 3, 4 refers X(6600), X(6900), X(7100)

- Other sequential indexing, such as $n = 1, 2, 3$, will produce equivalent results
- Consistent with Regge trajectory
  ==> a family of radial excitations

➢ *Can we gain further insight?*



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Interpretation and discussion

- Basic information: $P = (+)(-1)^L \quad C = (-1)^{L+S}$
- Constrain from X decay to J/ψJ/ψ : $J^{PC}_{J/\psi} = 1^{--}$

  C is conserved in strong decays, $C_X = (-1)(-1) = +1$

- **Under S-wave:** L = 0 → P = +1, J = S
  - In spin-0 diquark model, S = 0; **0++**
  - In spin-1 diquark model, S = 0, 1, 2; L+S should be even to make C positive; **0++, 2++**

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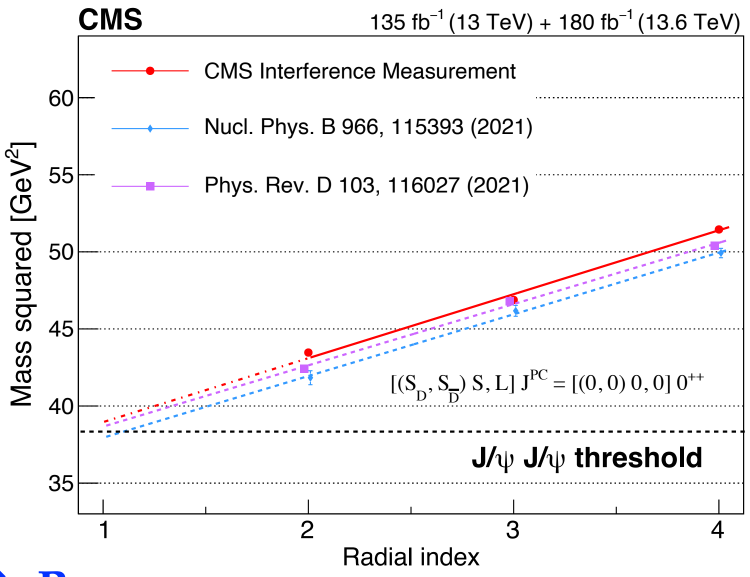
- **Under P-wave:** L = 1 → P = -1
  - In spin-0 diquark model, S = 0, makes C = -1, exclusive
  - In spin-1 diquark model, S = 0, 1, 2;

    L+S should be even to make C positive, S can only be 1, **0-+, 1-+, 2-+**
- **Under D-wave:** L = 2 → P = +1
  - In spin-0 diquark model, S = 0, **0++, 1++, 2++**
  - In spin-1 diquark model, S = 0, 1, 2; L+S should be even, S can be 0 or 2 **2++**

    0++, 1++, 2++, 3++, 4++

❖ S-wave


CMS
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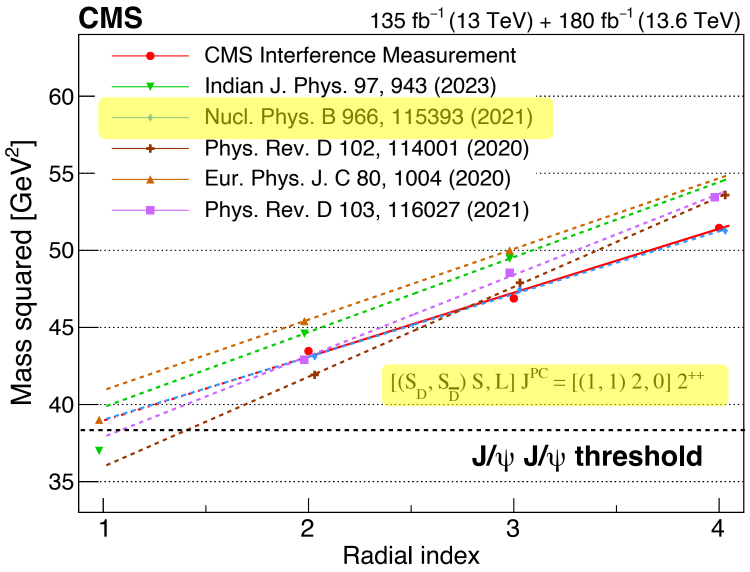
CMS Interference Measurement
Nucl. Phys. B 966, 115393 (2021)
Phys. Rev. D 103, 116027 (2021)
$[(S_D, S_{\bar{D}})\, S, L]\, J^{PC} = [(0,0)\, 0, 0]\, 0^{++}$
J/ψ J/ψ threshold
Mass squared [GeV^2]
Radial index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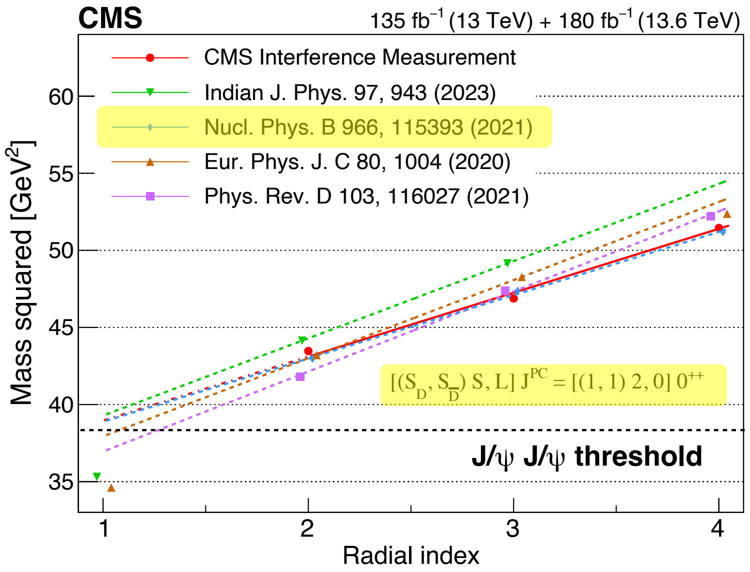
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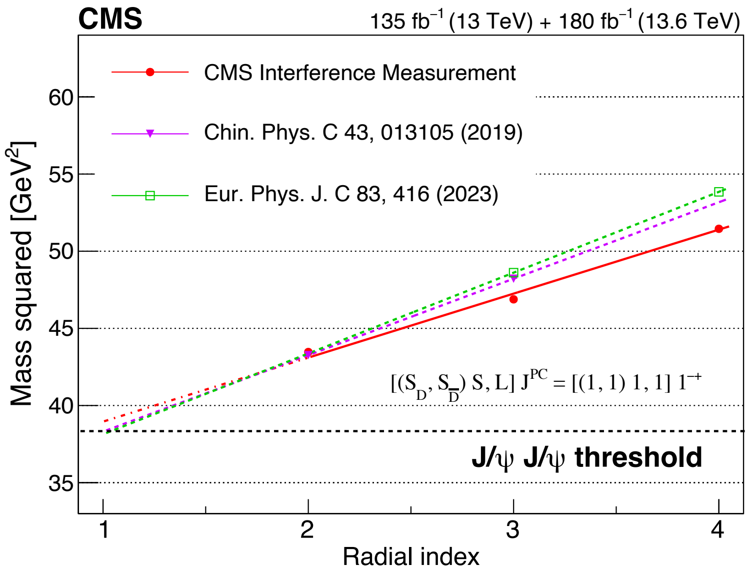
❖ P-wave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Mass squared [GeV^2]
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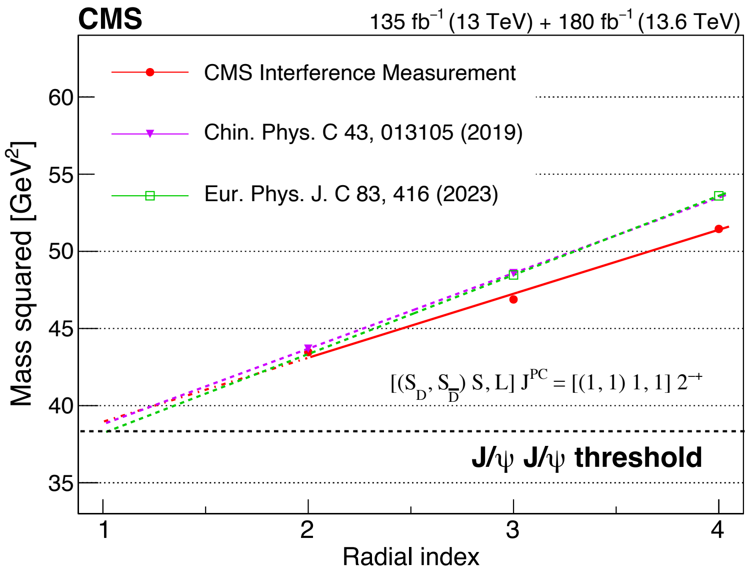
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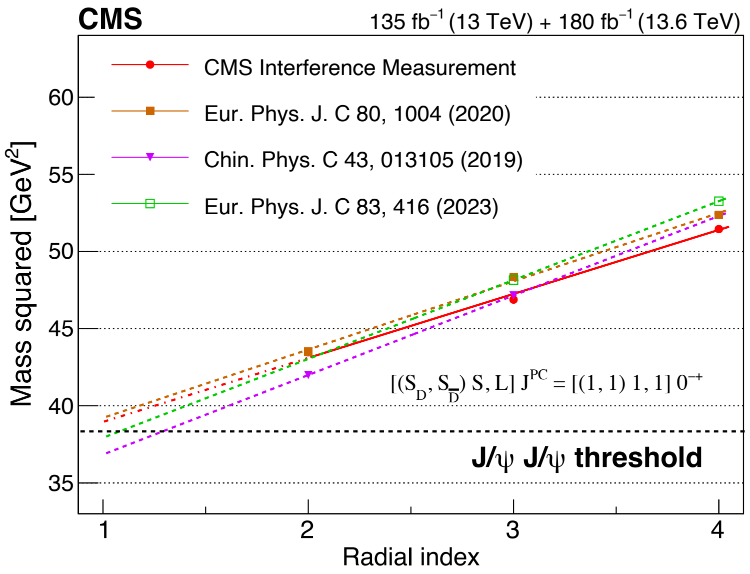
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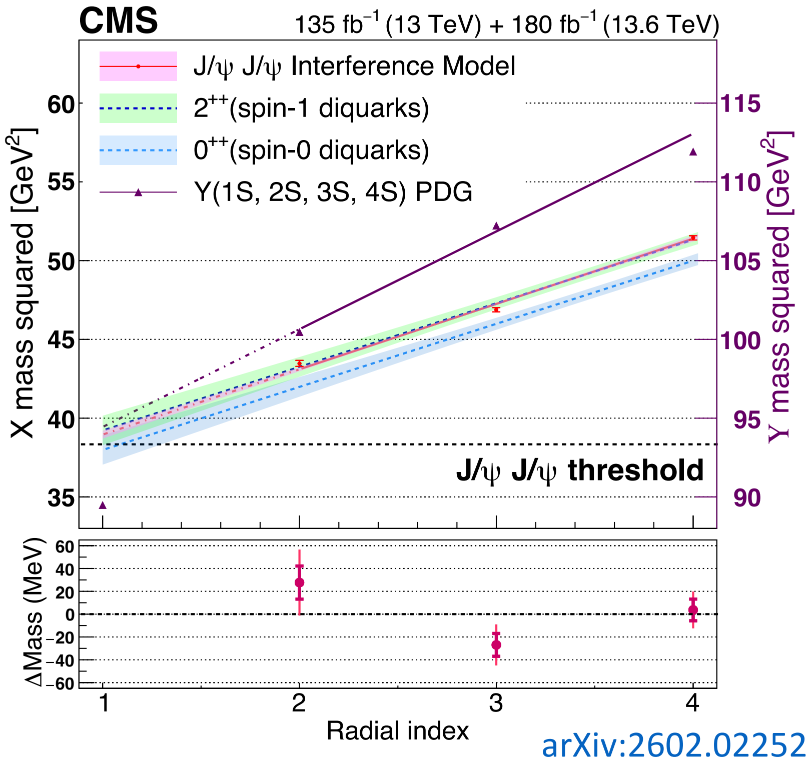
Chin. Phys. C 43, 013105 (2019)
Eur. Phys. J. C 83, 416 (2023)
$[(S_D, S_{\bar{D}})\, S, L]\, J^{PC} = [(1,1)\, 1, 1]\, 0^{-+}$
J/ψ J/ψ threshold
Mass squared [GeV^2]
Radial index

❖ In Regge theory : $n_r = \beta M^2 + \beta_0$

$n_r = n - 1$, radial quantum number n

Regge trajectories of X and ϒ

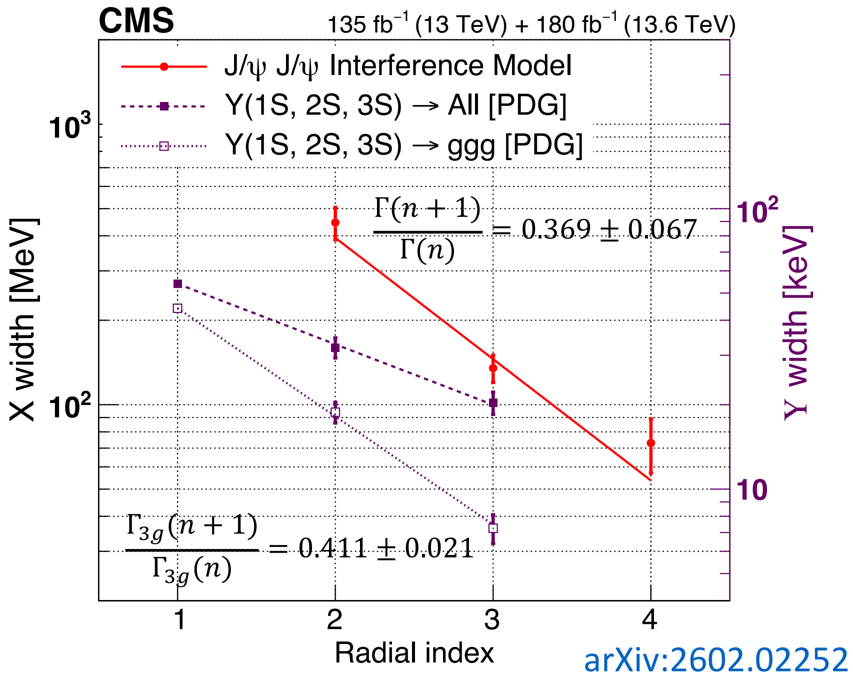


arXiv:2602.02252

🔎Good agreement with **spin-1 diquark** 0++ or 2++ state Nucl. Phys. B 966 (2021) 115393

❖ X widths decrease with radial excitation, exponentially

Widths trend of X and ϒ



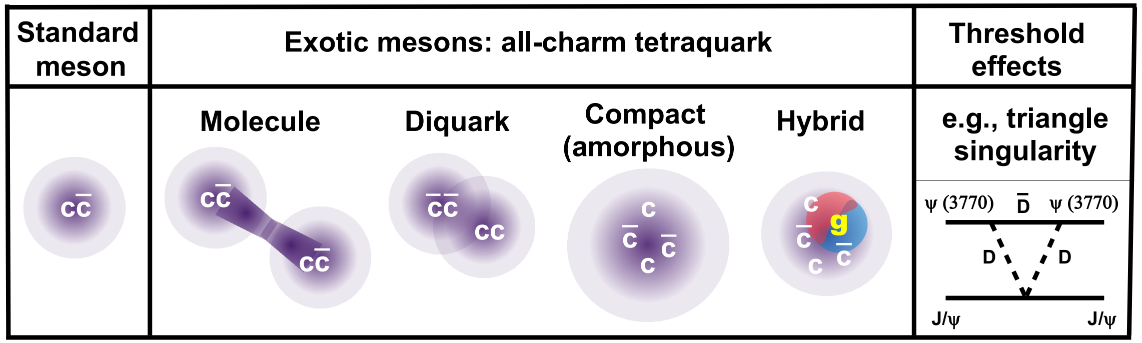
arXiv:2602.02252

In **ϒ** family, $b\bar{b}$ quark-antiquark annihilation predominantly

🔎 Suggest **a similar decay mechanism** for X states a sort of diquark-antidiquark "annihilation"

❖ Interpretation and discussion

★ Idealized models of all-charm structures theoretically
Molecular, Diquark-antidiquark, "amorphous" systems, hybrid…



❍ molecular or threshold interpretations

Governed by underlying charmonium pairs

Numerous pairings possible

Linear Regge and widths trends not expected

❍ "amorphous" systems

Lack of theoretical guidance

❍ hybrid models

Theoretical prediction not consistent

✓ Diquark-antidiquark model

★ Squared masses of triplet align Regge trajectory
==> Radial excitations

★ Regge match predictions for spin-1 (anti)diquarks with J^{PC} of 0^{++} or 2^{++}
0^{++} is less prominent in production than 2^{++}
arXiv:2006.14388
arXiv:2009.08376

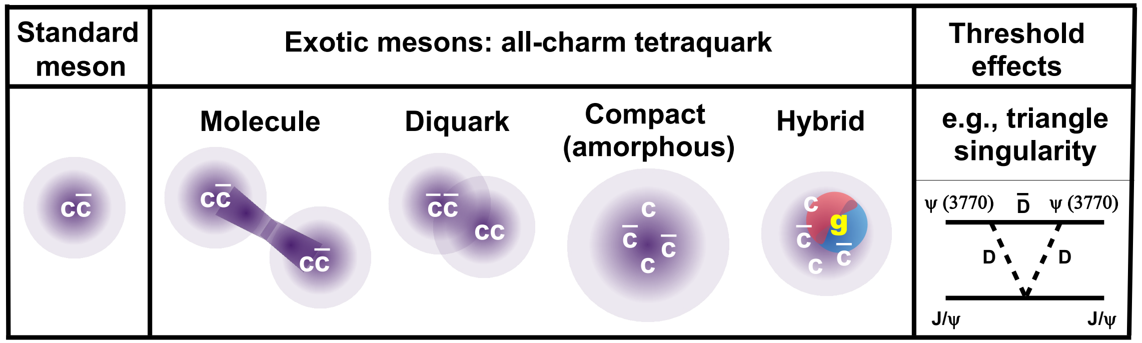
★ Widths decrease similar to Υ $b\bar{b}$ annihilation
"diquark-onium"

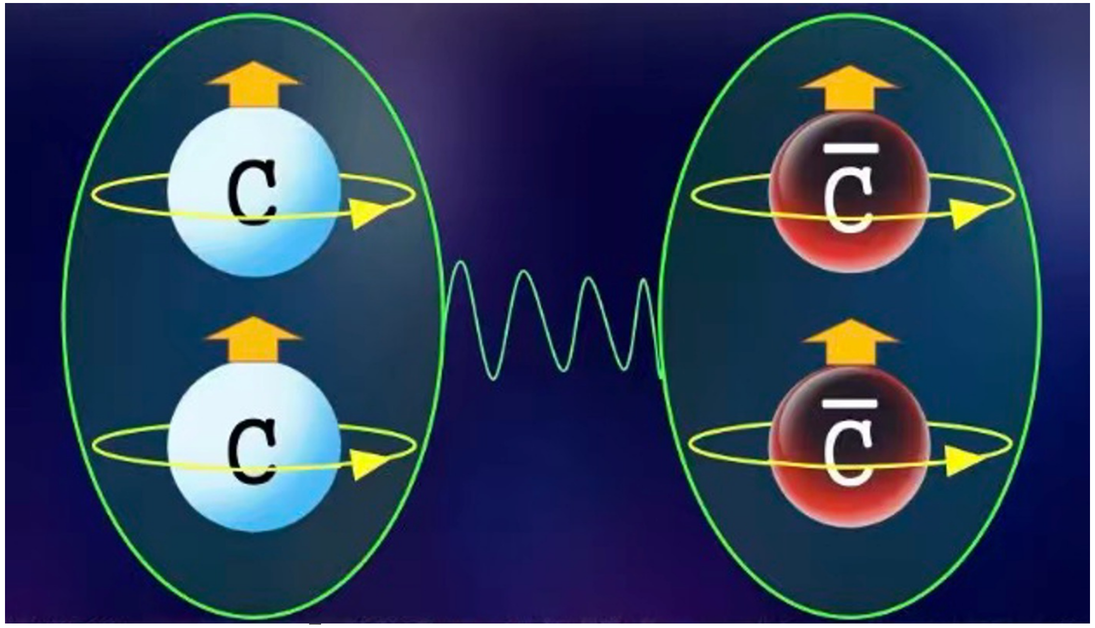
★ CMS angular analysis favors $J^{PC} = 2^{++}$

★ No orbital angular momentum ($L_{[cc][\bar{c}\bar{c}]} = 0$)
high orbital less likely, difficult to produce

❖ Interpretation and discussion

- ★ Idealized models of all-charm structures theoretically
  Molecular, Diquark-antidiquark, "amorphous" systems, hybrid…





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  high orbital less likely, difficult to produce

A system of aligned spin-1 diquarks forms a triplet of radially excited n^5S_2 states of $T_{cc\bar{c}\bar{c}}$

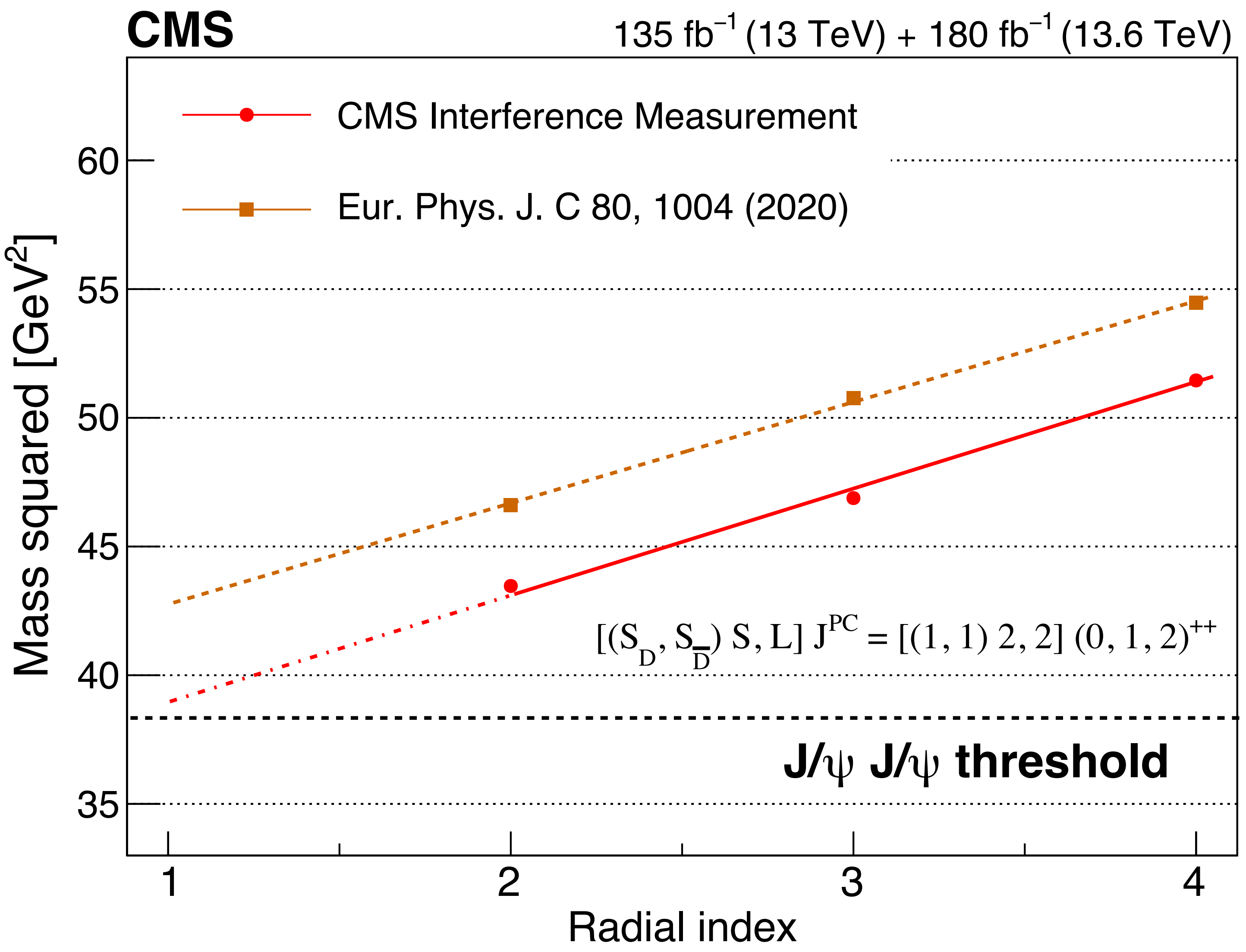
- A radial family of all-charm tetraquarks with same $J^{PC} = 2^{++}$
  - Three structures X(6600), X(6900), X(7100) established with significances > 5σ
  - Quantum interference among structures validated with significances > 5σ
  - First preliminary picture of the internal structure of this family.

Thanks to trigger strategy deployed during Run 3, a lot more exciting results are on their way!

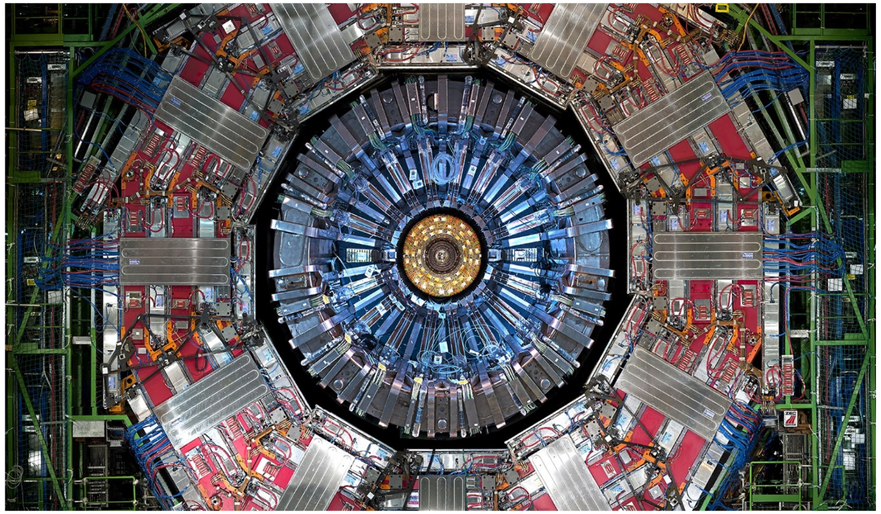
We are painting a coherent picture of Fully-heavy exotic hadrons

THANKS!

Backup


CMS
135 fb^{-1} (13 TeV) + 180 fb^{-1} (13.6 TeV)
CMS Interference Measurement
Eur. Phys. J. C 80, 1004 (2020)
[(S$_D$, S$_{\bar{D}}$) S, L] J^{PC} = [(1, 1) 2, 2] (0, 1, 2)$^{++}$
J/ψ J/ψ threshold
Mass squared [GeV^2]
Radial index
60
55
50
45
40
35
1
2
3
4

The CMS Detector



❖ **Excellent detector for quarkonium studies with muons**

Muon system

High-purity muon ID, $\Delta m/m \sim 0.6\%$ for J/ψ

Silicon Tracking detector B=3.8T

$\Delta p_T/p_T \sim 1\%$ & excellent vertex resolution

❖ **Majority of analyses rely on dimuon triggers**

Flexible trigger system for different analyses

Overview of CMS Trigger System

Collisions at 40 MHz

Level 1 Trigger (L1)
Coarse reconstruction, limited detector systems, hardware-based (ASIC/FPGA)

100 kHz

High Level Trigger (HLT)
Full detector information and online resolution, software-based (CPU/GPU)

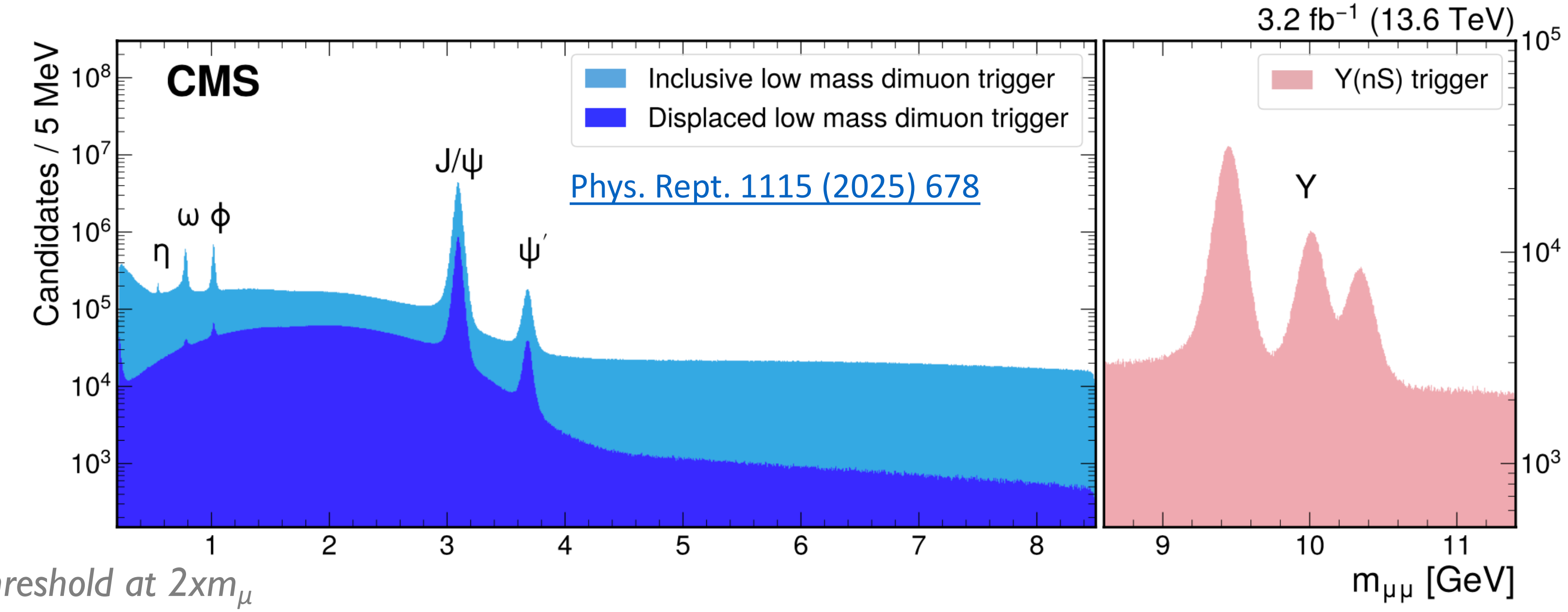
~1.5 kHz → **Standard Stream** *Immediate offline reco*

~3 kHz → **Parking Stream** *Delayed offline reco*

~15 kHz → **Scouting Stream** *No offline reco*

- Save RAW event, contains complete detector information, no reconstruction
- Uses less computational resources, enabling higher rates and lower kinematic thresholds

- Parking streams are a game-changing effort for CMS flavour physics
- Expanded physics potential thanks to inclusive dimuon parking dataset



di-μ mass lower threshold at $2xm_\mu$

- Broad low-mass μμ reach with minimal kinematic & topology requirements

  overcome limitations requiring additional tracks, mass range and vertexing
- Rate controlled via delayed reconstruction and kinematic thresholds dynamic release only at L1T

CMS have opened new opportunities in flavour physics!

Diquark view

❖ In the diquark–antidiquark picture, diquark is a bound system of fermions, Pauli principle requiring the overall diquark wave function to be antisymmetric

$$\Psi_{\text{diquark}} = \psi_{\text{space}} \times \psi_{\text{color}} \times \psi_{\text{flavor}} \times \psi_{\text{spin}} \equiv \Psi_{\text{antisym.}}.$$

- **The parity of the spatial part** of the wave function is determined by the angular momentum L

$$P = (-1)^{L}$$

Most of the theoretical paper consider only the ground state diquarks.
Because excitations within the diquark or antidiquark increase the diquark mass and size, providing a larger overlap between the diquark and antidiquark which enhances the rapid fall-apart strong decay processes.
And this may result these states have less chances to be observed as resonances.

- **Fall-apart strong decay**: the quarks and antiquarks from the initial tetraquark rearrange into two mesons

$$\mathrm{Q_1 Q_2 \overline{Q}_3 \overline{Q}_4} \longrightarrow \mathrm{Q_1 \overline{Q}_3} + \mathrm{Q_2 \overline{Q}_4}.$$

If energetically possible and isn't forbidden by the quantum numbers, this is the main decay channel.
As the state can decay very rapidly, it could be observed as a broad resonance in this channel.

$$P_{\text{ground state}} = (-1)^{L_{\text{ground state}}} \equiv (-1)^0 = 1,$$
$$\Longrightarrow \psi_{\text{space}} \equiv \psi_{\text{sym.}}.$$

The parity of the spatial part is symmetric

❖ In the diquark–antidiquark picture, diquark is a bound system of fermions, Pauli principle requiring the overall diquark wave function to be antisymmetric

$$\Psi_{\text{diquark}} = \psi_{\text{space}} \times \psi_{\text{color}} \times \psi_{\text{flavor}} \times \psi_{\text{spin}} \equiv \Psi_{\text{antisym.}}.$$

- **The color part** of the wave function depends on the choice of the color representation of the diquark.

Two quarks are two color triplets, in combination they give two irreducible representations,
either a color symmetric sextet or an antisymmetric antitriplet

$$3 \times 3 = 6 \oplus \bar{3},$$
$$\bar{3} \times \bar{3} = \bar{6} \oplus 3.$$

In color-sextet representation the internal interaction between the quarks within the diquark is repulsive, which means that it cannot be a bound state.
For a color-antitriplet diquark, the interaction between the quarks is attractive, thus, choose the color-antitriplet for the further considerations.

$$\psi_{\text{color}} \equiv \psi_{\text{antisym.}}.$$

The parity of the color part is antisymmetric

Note: quark–antiquark cross diquark–antidiquark interactions could stabilize sextet–antisextet diquarks.

Diquark view

- In the diquark–antidiquark picture, diquark is a bound system of fermions, Pauli principle requiring the overall diquark wave function to be antisymmetric

symmetric

$$\Psi_{\text{diquark}} = \psi_{\text{space}} \times \psi_{\text{color}} \times \psi_{\text{flavor}} \times \psi_{\text{spin}} \equiv \Psi_{\text{antisym.}}.$$

antisymmetric

- The combination of the flavor and spin parts of the diquark wave function should be symmetric

$$\psi_{\text{flavor}} \times \psi_{\text{spin}} \equiv \psi_{\text{sym.}}.$$

In all-charm tetraquark system, same flavor with **the symmetric flavor part**

It can only be axialvector with **the symmetric spin part**

$$\text{spins } S_{\text{d}} = 1$$

$$\begin{cases} \psi_{\text{flavor}} = \psi_{\text{sym.}}, \\ \psi_{\text{spin}} = \psi_{\text{sym.}}, \end{cases}$$

That's the reason why most of theory paper usually focus more on spin-1 diquark model.
However, if ***the color part*** *chosen the color symmetric sextet, spin-0 diquark can also appear.*

Diquark view

- Basic information: $P = (+)(-1)^L \quad C = (-1)^{L+S}$
- Constrain from X decay to JpsiJpsi: $J^{PC}_{J/\psi} = 1^{--}$

C is conserved in strong decays, $C_X = (-1)(-1) = +1$

- **Under S-wave:** L = 0 → P = +1, J = S
  - In spin-0 diquark model, S = 0, X's JPC can only be 0++
  - In spin-1 diquark model, S = 0, 1, 2; L+S should be even to make C positive, S can not be 1, X's JPC can be 0++, 2++.
- **Under P-wave:** L = 1 → P = -1
  - In spin-0 diquark model, S = 0, makes C = -1, exclusive
  - In spin-1 diquark model, S = 0, 1, 2;

    L+S should be even to make C positive, S can only be 1, X's JPC can be 0-+, 1-+, 2-+
- **Under D-wave:** L = 2 → P = +1
  - In spin-0 diquark model, S = 0, X's JPC can be 0++, 1++, 2++
  - In spin-1 diquark model, S = 0, 1, 2; L+S should be even, S can be 0 or 2

If S = 0, X's JPC can only be 2++

If S = 2, X's JPC can be 0++, 1++, 2++, 3++, 4++

Comparison with other Regge predictions